REPORT DOCUMENTATION PAGE

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	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Robert Behringer	5d. PROJECT NUMBER
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	5f. WORK UNIT NUMBER

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13. SUPPLEMENTARY NOTES

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14. ABSTRACT

This project, with Antoinette Tordesillas of U of Melbourne, investigated models for the upper soil surface and its response to applied loads. We have examined key aspects above, experimentally and with computer simulations. We developed new micromechanically-based continuum models with predictive capabilities for multiscale phenomena in the soil/granular liquid-solid regime, based on the experiments and simulations. The Duke work involved detailed experiments that provided detailed information about the collective and local properties of

15. SUBJECT TERMS

Granular materials, force chains, jamming, networks, soil stability

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Behringer
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Report Title

Final Report:
Multiscale Phenomena in the Solid-Liquid Transition State of a Granular Material Proposal Number 51923-EV

ABSTRACT

This project, with Antoinette Tordesillas of U of Melbourne, investigated models for the upper soil surface and its response to applied loads. We have examined key aspects above, experimentally and with computer simulations. We developed new micromechanically-based continuum models with predictive capabilities for multiscale phenomena in the soil/granular liquid-solid regime, based on the experiments and simulations. The Duke work involved detailed experiments that provided detailed information about the collective and local properties of granular materials subject to shear and compression. We have shown that the jamming of granular materials is fundamentally different than for other frictionless particular systems. In collaboration with Antoinette Tordesillas, and using our photoelastic experiments, we have developed and tested a new stability method for characterizing granular materials, specifically at the level of clusters and networks.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2011/11/29 1· 5	T. S. Majmudar, M. Sperl, R. P. Behringer, Jie Zhang. Jamming for a 2D granular material, Soft Matter, (06 2010): 0. doi: 10.1039/c000147c
2011/11/29 1· 3	Antoinette Tordesillas, Colin Thornton, Robert P. Behringer, David M. Walker, Jie Zhang, John F. Peters. Percolating contact subnetworks on the edge of isostaticity, Granular Matter, (02 2011): 0. doi: 10.1007/s10035-011-0250-y
2011/11/29 1· 2	Jie Zhang, Robert Behringer, Antoinette Tordesillas. Buckling force chains in dense granular assemblies: physical and numerical experiments, Geomechanics and Geoengineering, (03 2009): 0. doi: 10.1080/17486020902767347
2011/11/28 1· 7	J. Zhang, T. S. Majmudar, A. Tordesillas, R. P. Behringer. Statistical properties of a 2D granular material subjected to cyclic shear, Granular Matter, (03 2010): 0. doi: 10.1007/s10035-010-0170-2
2011/11/28 1· 6	Qun Lin, Jie Zhang, R.P. Behringer, Jingyu Shi, Antoinette Tordesillas. Structural stability and jamming of self-organized cluster conformations in dense granular materials, Journal of the Mechanics and Physics of Solids, (02 2011): 0. doi: 10.1016/j.jmps.2010.10.007

TOTAL: 5

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Sixteen invited talks including colloquia, seminars and professional meetings

Number of Presentations: 16.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2011/11/29 1(	9	J. Zhang, J. Ren, S. Frahadi, R,P. Behringer. A Dense 2D Granular Material Subject to Cyclic Pure Shear, Powders and Grains, 2009. 2009/07/13 00:00:00, . : ,

TOTAL: **1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2011/11/28 1·	10	J. Krim, Peidong Yu, R. P. Behringer. Stick-Slip and the transition to Steady Sliding in a 2D Granular Medium and a Fixed Particle Lattice, Pure and Applied Geophysics (11 2011)
2011/11/28 1·	8	Peidong Yu, Trevor Shannon, Brian Utter, R. P. Behringer. Stick-Slip in a 2D Granular Medium, Granular Matter (06 2009)
2011/11/28 1·	4	D. Bi, J. Zhang, B. Chakraborty, R. P. Behringer. Jamming by Shear, Accepted for Nature, October, 2011 (11 2011)

TOTAL: **3**

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Peidong Yu	0.60	
FTE Equivalent:	**0.60**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Jie Zhang	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert Behringer	0.08	
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Peidong Yu	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

TERRESTRIAL SCIENCES PROJECT BIENNIAL PROGRAM REVIEW REPORTING

Summary of Accomplishments, Final Project Report: Multiscale Phenomena in the Solid-Liquid Transition State of a Granular Material

Proposal Number 51923-EV

Robert P. Behringer
Department of Physics
Duke University

Background for Summary of Accomplishments

Experiments were carried out at Duke University which exploited the special properties of photoelastic materials. These materials, plus the expertise developed by the PI and his group, allowed for the detailed particle-scale determination of all physically relevant properties of a model granular system at the grain scale. Specifically, for every particle, we measured displacements, rotations and all contact forces. This approach allows experimental information at all scales within a granular material. From these properties, it was possible to compute stresses and other quantities that are relevant at the macroscopic scale, which are important to vehicle mobility and other important issues for the Army. To our knowledge, the Duke lab is the only facility anywhere which is capable of this type of measurement. Experiments were carried out in several specific settings:

- *Traction on a granular surface--A key issue involved traction and the response of a granular material to a moving object on its surface. A set of experiments involved pulling an object across the surface of a layer of photoelastic particles. Simultaneous measurements were made of the pulling force and the photoelastic response of the granular layer. It was then possible to correlate the slipping behavior of the object to the internal response of the granular material.*
- *The nature of failure under shear--Perhaps the most important failure mode for granular materials occurs when they are subject to shear. This is important in the vehicle-like experiments above, and also for a granular/soil surface that is loaded by heavy objects. A second set of experiments, in coordination with the theoretical and DEM studies of Antoinette Tordesillas, focused on the multiscale nature of failure under shear. In this case, the experiments again exploited the special properties of particles that were made from a photoelastic material. The particles were contained in a biaxial device whose purpose was to provide highly controlled shear or other stresses. Again, all physically relevant properties were accessible via this approach. A particularly interesting recent finding from this work, discussed below, was the observation that loosely packed unstable soils can be stabilized, i.e. jammed, by the application of shear. To my knowledge, this is a quite new finding that will require a rethinking of the widely accepted picture of jamming. Additional experiments of this type are continuing.*
- ***A project that involved studies of simple shear that was carried out over many cycles, again using photoelastic particles has been launched. Data from these experiments test/inform models under development with Antoinette Tordesillas.***

- ***A project that involves an extension of the 2D experiments to 3D has been launched. This required a sophisticated new apparatus, which has largely been constructed by post-doc Joshua Dijksman.***
- *Parallel simulations were carried out by A. Tordesillas of the University of Melbourne, Australia. This work also involved the development of new types of continuum or mixed continuum—discrete models which are based on the experiments and simulations.*

Details of Accomplishments

- In collaboration with Antoinette Tordesillas, and using our photoelastic experiments, we developed and tested a new stability method for characterizing granular materials, specifically at the level of clusters. (paper published: Antoinette Tordesillas, Qun Lin, Jie Zhang, R. P. Behringer and Jingyu Shi, Journal of the Mechanics and Physics of Solids **59**, 265--296 (2011): Percolating contact subnetworks on the edge of isostaticity, D.M. Walker, A. Tordesillas, C. Thornton, R. P. Behringer, J. Zhang, and J. F. Peters, Granular Matter to appear (2011))
- Also, with Antoinette Tordesillas and other collaborators, we applied novel ideas from network theory, in combination with the stability criterion from the previous point, to characterize the dynamical evolution of the force network in granular materials.
- We developed and used a slider/friction experiment that yielded high quality information about the nature of granular stick-slip and the transition to sliding under surface traction. In particular, these results should lead to new insights into what is meant by granular friction. These data showed that granular materials fail under traction by a process that dissipates energy relatively deeply in the material, rather than just at the surface. In addition, the data characterized in detail the nature of granular slip and suggested ways to maximize traction/avoid slip under a vehicle. These experiments also informed researchers about the dynamics of stick-slip in earthquake fault zones. In this regard, the energy losses for stick-slip events are power-law distributed, in analogy to the Gutenberg-Richter law for earthquake magnitudes. However, the powerlaw that we observe for the probability distribution function (PDF) for energy losses has an exponent of about 1.2, whereas the typical GR exponent is about 5/3 (when represented as a PDF for energy losses).

- Extensive experiments characterized in detail the behavior of a granular material that was subject to pure shear and pure cyclic shear. These data included detailed results for particle properties, including contact forces and particle displacements, as well as macroscopic results such as stresses. Of particular note is the observation that dilated weak granular materials can jam, i.e. become solid-like, under shear. This result has required significant rethinking of the proposed model jamming diagram of Liu and Nagel, which proposed that the lowest density (e.g. dilated) state of the system that is jammed is an isotropic one. A particularly interesting observation for cyclic shear, starting from an unjammed low density isotropic state is that over many cycles, the pressure, the shear stress and the mean number of contacts per particle are all linearly related. This work has appeared in Granular Matter, and a Letter will appear in Nature at the end of 2011.
- We have developed a new experimental approach that allows the determination of photoelastic information and of particle motions without mutual interference. This both speeds up measurements and ensures that data for forces and for particles motions will be obtained for identical situations.
- We have developed automated data taking methods to streamline the process of collecting large image data sets.

- We have worked with Evidence Design to build a very novel science demonstration at the Museum of Science and Industry, per the photo below.